EEC, ERI: A Mixed-Methods Study of Decision-making Under Variability

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This short report gives an update on the NSF-supported project “ERI: Towards Data-Capable Engineers with a Variability-Capable Mindset” (Grant No. 2138463).

Variability is a key statistical phenomenon, but it is under-emphasized in engineering education. A recent review of education research on mathematical practices in engineering found that only 2 out of 5,466 articles discussed "uncertainty" or "error" [1]. A scoping review of actively-used engineering textbooks found that only 11% mention "variability". Given this gap in the literature, the NSF funded this project to better understand decision-making under variability, particularly as it pertains to engineering.

The early qualitative phase of this project produced a taxonomy to describe engineers' decision-making under variability. This *NAT Taxonomy* is described elsewhere [2], but in short, the taxonomy consists of three nested rungs:

1. Neglected: Participant’s analysis neglects the existence of variability, usually by reporting a single value.
2. Acknowledged: Participant’s analysis acknowledges the existence of variability, but does not respond to the consequences of variability.
3. Targeted: Participant’s analysis responds to the consequences of variability.

Targeting variability is the top rung of the NAT Taxonomy, and it usually corresponds to making conservative choices in response to variability. For instance, when analyzing a structure for failure it is usually conservative to assume that a material has a lower strength than its typical value, while it is usually conservative to assume a larger loading than the nominal load.

The latter quantitative phase of this project produced a survey-based instrument to measure decision-making under variability according to the NAT Taxonomy. The NAT Instrument's iterative design [3] and evidence for reliability and validity [4] are reported elsewhere. Using this research product, engineering educators can now incorporate the instrument and its ideas as a component of other studies. To illustrate this, we report pilot results from an interdisciplinary research project using the NAT Instrument to study student behavior in an authentic engineering task.

We conducted an exploratory study of engineering students' decision-making in an authentic engineering task: a "design challenge" where undergraduate engineering students designed a bike frame navigating competing objectives of minimal deformation and minimal environmental impact—more material minimizes deformation, while less material minimizes environmental impact. The hackathon lasted about an hour and had students use a combination of computer-aided design software (Onshape) to design the bike frame, and a spreadsheet tool (in Google Sheets) to compute embodied carbon and record each design iteration's performance. The activity lasted about an hour, and 11 participants consented to participate (Brandeis IRB, Protocol #26027R-E).

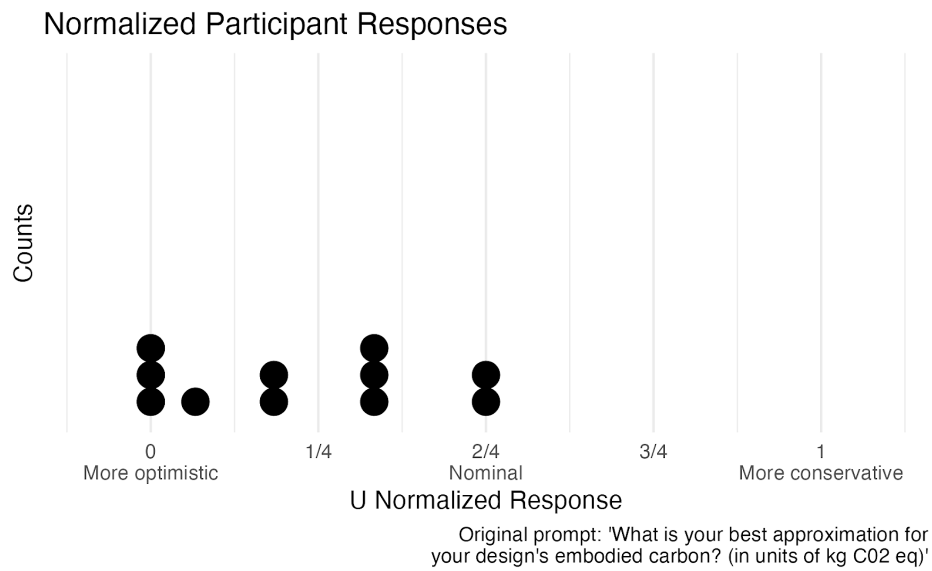

Figure 1. Normalized participant responses for "best approximation" embodied carbon.

We incorporated the NAT Instrument in an exit survey to characterize students' general decision-making under variability in everyday scenarios, compared against base rates measured among U.S. adults [4]. For brevity, we used a four-task subset of the full instrument, with task comprehension rates (100% in most cases) much higher than the typical 80% comprehension rate among U.S. adults. Five of 11 participants targeted variability on all tasks, similar to the 40% base rate found among U.S. adults. Thus, students in the sample are no less (and no more) adept at making decisions under variability than the general U.S. population.

The hackathon task's design was inspired in part by the NAT Instrument: We provided students with material property data (specific embodied carbon) in the form of both typical (e.g., 10 g CO2eq/g) and range (e.g., 7—13 g CO2eq/g) information. Students used the data to analyze each design iteration's embodied carbon, but had to determine how to use the provided information (typical value and range). In the exit survey, we requested a numerical value from participants with the prompt "What is your best approximation for your design's embodied carbon? (in units of kg C02 eq)". We additionally asked for a high and low estimate ("Please give the (**lowest|highest**) reasonable approximation for your design's embodied carbon (in units of kg C02 eq)."). Since one of the design objectives was to minimize embodied carbon, a conservative estimate for performance would be a value near the participant's reported higher value.

Figure 1 displays participants' "best" answer, normalized to lie between [0, 1] using the participant's high and low estimates. These results demonstrate an ambiguity in student interpretation of "best:" Three students gave a response at their lowest value—an optimistic response. Two students gave a response at their middle value—a nominal response. The remaining six students gave a response between optimistic and nominal.

Surprisingly, zero students gave a conservative response for their final design embodied carbon (Fig. 1). This is in contrast with their demonstrated ability to make conservative decisions in everyday scenarios (on the NAT Instrument), and could be problematic in a consequential engineering setting. Given the "challenge" framing of the activity, students' propensity to give an optimistic final design assessment is understandable. However, inspection of their per-iteration analyses shows a more concerning trend.

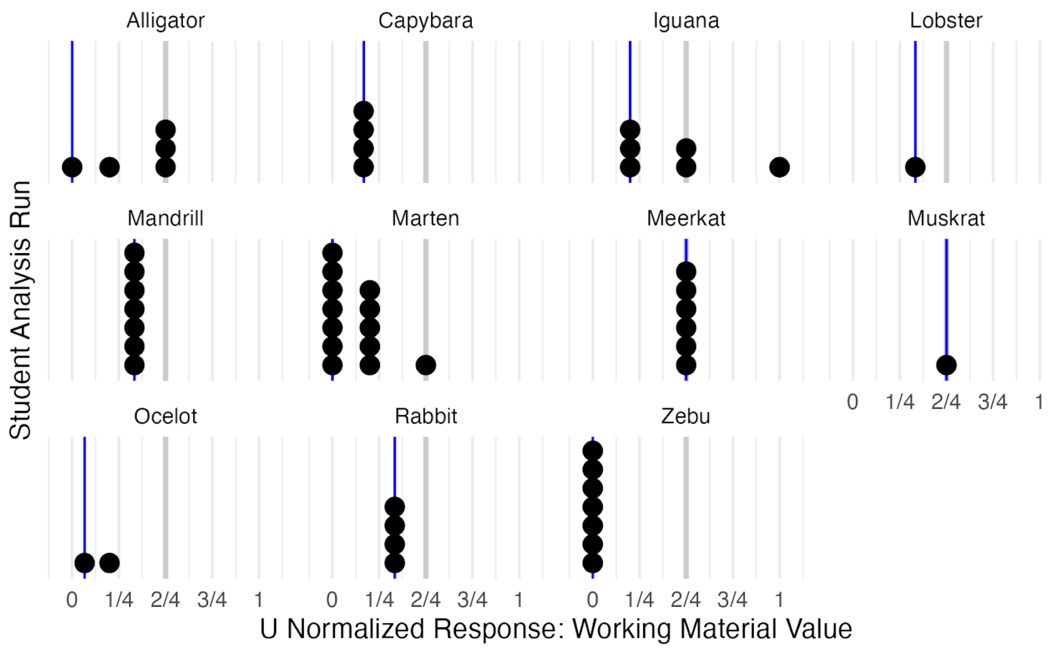

Figure 2. Normalized working value for specific embodied carbon, for each analysis (dot) and each participant (panel). Participant's normalized "best approximation" values shown as blue vertical lines.

Figure 2 reports participants’ "working" values: the material property value a participant chose during the workshop to analyze a particular iteration. Using the same [0, 1] normalization, we can see that participants' working value selection logic generally followed their "best" value selection: nearly always between optimistic and nominal. Strikingly, we see that only one participant (codename Iguana) conducted an analysis with a conservative working value for the specific embodied carbon, and then only one of six of their analyses used a conservative value. While reporting optimistic final values for a "challenge" may be reasonable, the vast majority of participants did not conduct a single conservative analysis. This would be problematic in an engineering design setting, where a conservative consideration of variability would affect decisions such as material choice and determination of engineering margins.

Comparing the NAT Instrument results and engineering activity details (both from this design challenge), we see a striking difference in behavior. On the NAT Instrument, five of eleven participants targeted variability on all four tasks, and *all* participants targeted variability at least once. Participants made conservative choices in the face of variability regarding the everyday scenarios depicted in the NAT Instrument, despite generally *not* making conservative choices in the engineering design task. This failure-to-transfer is consistent with the under-emphasis of variability reported at the start of this report: Engineering training does not emphasize the consequences of variability, so students may not see a need to account for variability in engineering decision making. This could emerge from a lack of understanding of consequences (the impact of embodied carbon is more abstract than missing a meeting), or it could come from a general perception of irrelevance of variability in engineering [5]. It is important to note the small sample (n=11 students) from a single college prevents inference to a larger population; it is unclear how these results may compare with similar studies at other institutions. Future work could investigate the barriers to transfer (targeting from everyday scenarios to engineering scenarios), develop interventions to promote student targeting of variability, and adapt the NAT Instrument to measure intervention efficacy.

Acknowledgements
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References

[1] K. Hadley and W. Oyetunji, "Extending the Theoretical Framework of Numeracy to Engineers," *J. Eng. Educ.*, vol. 111, no. 2, pp. 376–399, Apr. 2022, doi: 10.1002/jee.20453.
[2] Z. del Rosario, "Neglected, Acknowledged, or Targeted: A Conceptual Framing of Variability, Data Analysis, and Domain Consequences," *J. Stat. Data Sci. Educ.*, 2024, doi: 10.1080/26939169.2024.2308119.
[3] Z. del Rosario, J. Ryu, and E. Saur, "Targeting Consequences of Variability as a Data Science Resource," presented at the IASE Roundtable Conference, Auckland, NZ: IASE, 2024. [Online]. Available: https://doi.org/10.52041/iase24.505
[4] Z. del Rosario, E. Saur, J. Ryu, J. Lin, and J. B. Wilmer, "DECISIONS, VARIATION, AND VISUALIZATION: A NOVEL INSTRUMENT FOR DECISION MAKING UNDER VARIABILITY," May 12, 2025, *PsyArXiv*. doi: 10.31234/osf.io/vujta_v1.
[5] L. Bostwick, A. George, T. Lee, and Z. del Rosario, "When Is It Relevant? A Collaborative Autoethnographic Study by Engineering Students on Statistical Variability," in *ASEE Annual Conference Proceedings*, Portland, OR, 2024.